Magnetic force microscopy of superconducting structures

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Introduction

Magnetic force microscopy (MFM) is one of the most precise and informative methods for studying magnetic properties and defects in superconductors. This metod provides high spatial resolution and allows for the analysis of structures, making it an essential tool in the study of diverse superconducting materials and devices.

This report discusses the basic principles of a magnetic force microscope and provides examples of studies using MFM of the magnetic properties of niobium films and the effect of a local gate on the properties of superconducting devices.

Principles of magnetic force microscopy

The principle of a MFM is based on the use of a magnetic cantilever that interacts with magnetic fields on the surface of a test sample.

The probe of a MFM consists of an elastic cantilever beam. One end of the cantilever is fixed, and the other is free and equipped with a magnetic coated tip. It is through this tip that the probe interacts with the sample.

When the probe moves over the surface of the sample, magnetic forces cause the cantilever to deflect. This deviation is recorded using an optical system, for example, a laser interferometer.

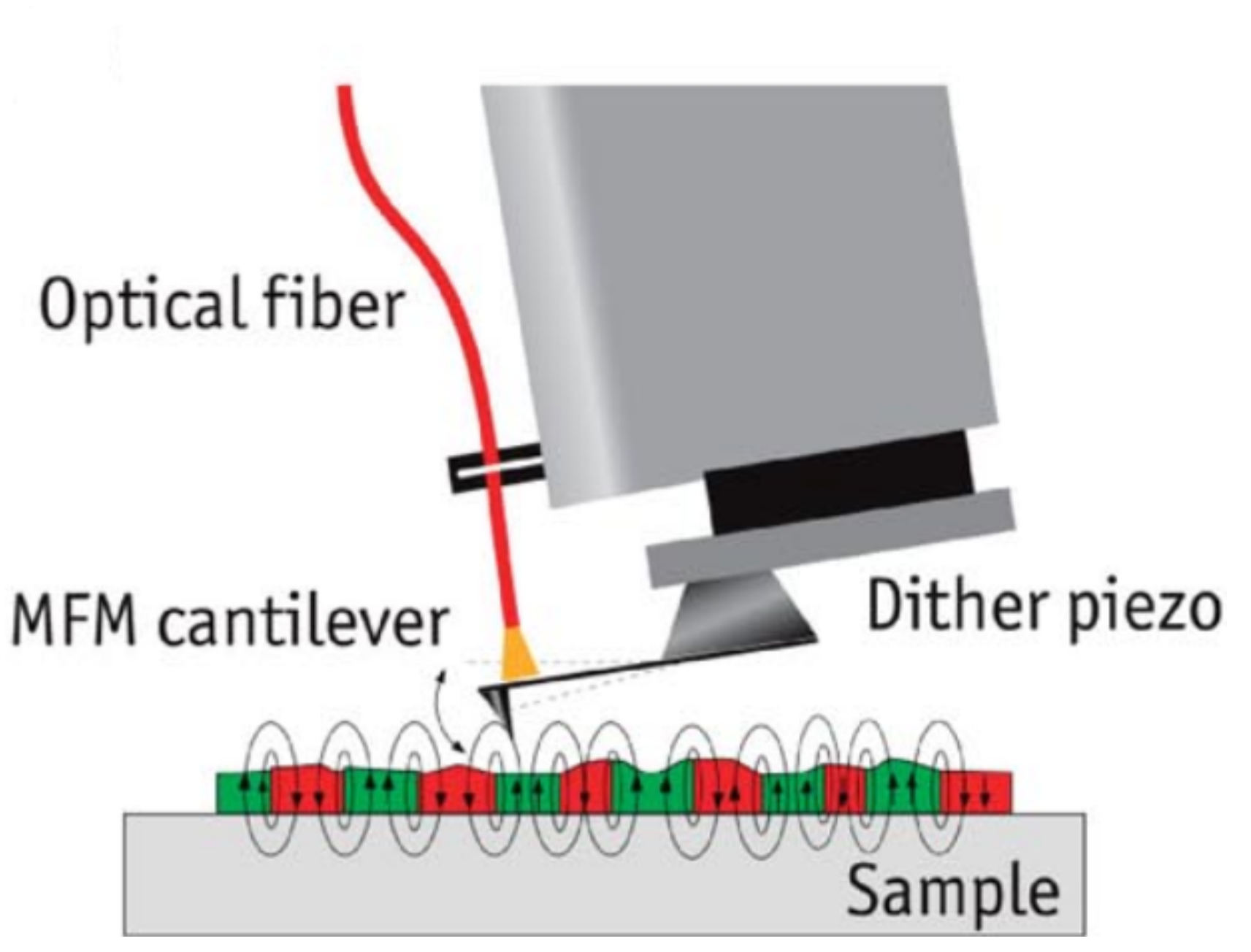
The main modes of operation of the MFM include:

1. **Static mode:** In this mode, the cantilever scans the sample surface at a certain distance ($h = const$), detecting deviations under the influence of local magnetic fields.
2. **Dynamic mode:** In this mode, the built-in piezoelectric vibrator is used to create vibrations in the cantilever at a frequency close to its resonance. As the probe sensor moves along the test surface, changes in the vibration parameters due to the magnetic interaction with the sample are recorded. The changes in the frequency, amplitude and phase of vibrations:

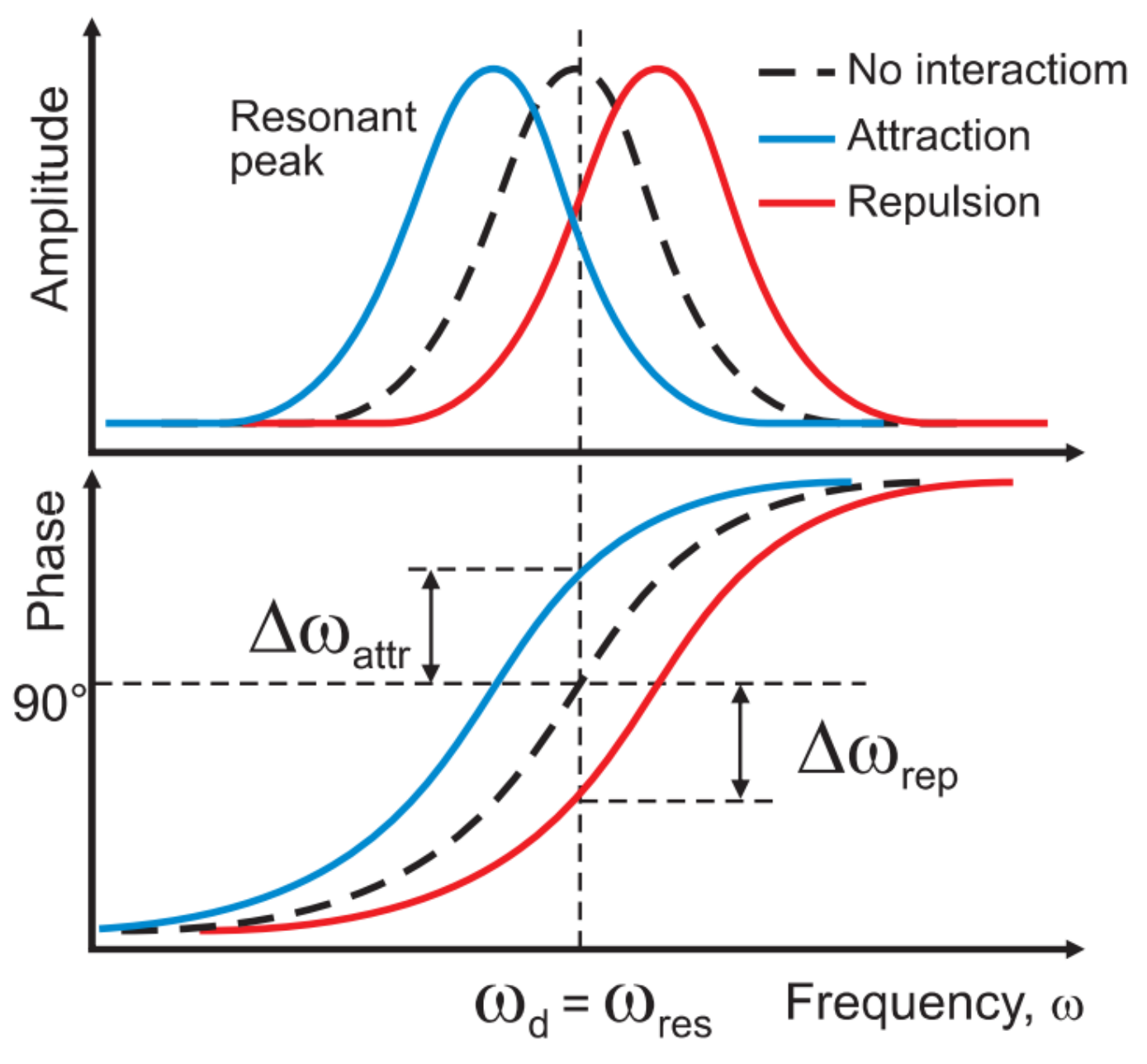
$$\Delta A \sim \frac{Q^2}{k}\frac{dF(z)}{dz} \qquad \Delta\phi \sim \frac{Q}{k}\frac{dF(z)}{dz}$$

   where Q is quality factor, F is the force with which the field acts on the cantilever
   The use of this mode makes it possible to realize better sensitivity (compared with static mode).
3. **Dual-Pass mode:** In the first pass, the topography of the surface is removed. In the second pass, the probe moves at a constant distance from the surface, following its relief. The use of this technique makes it possible to obtain MFM images of samples with a highly developed relief.

System of interest:

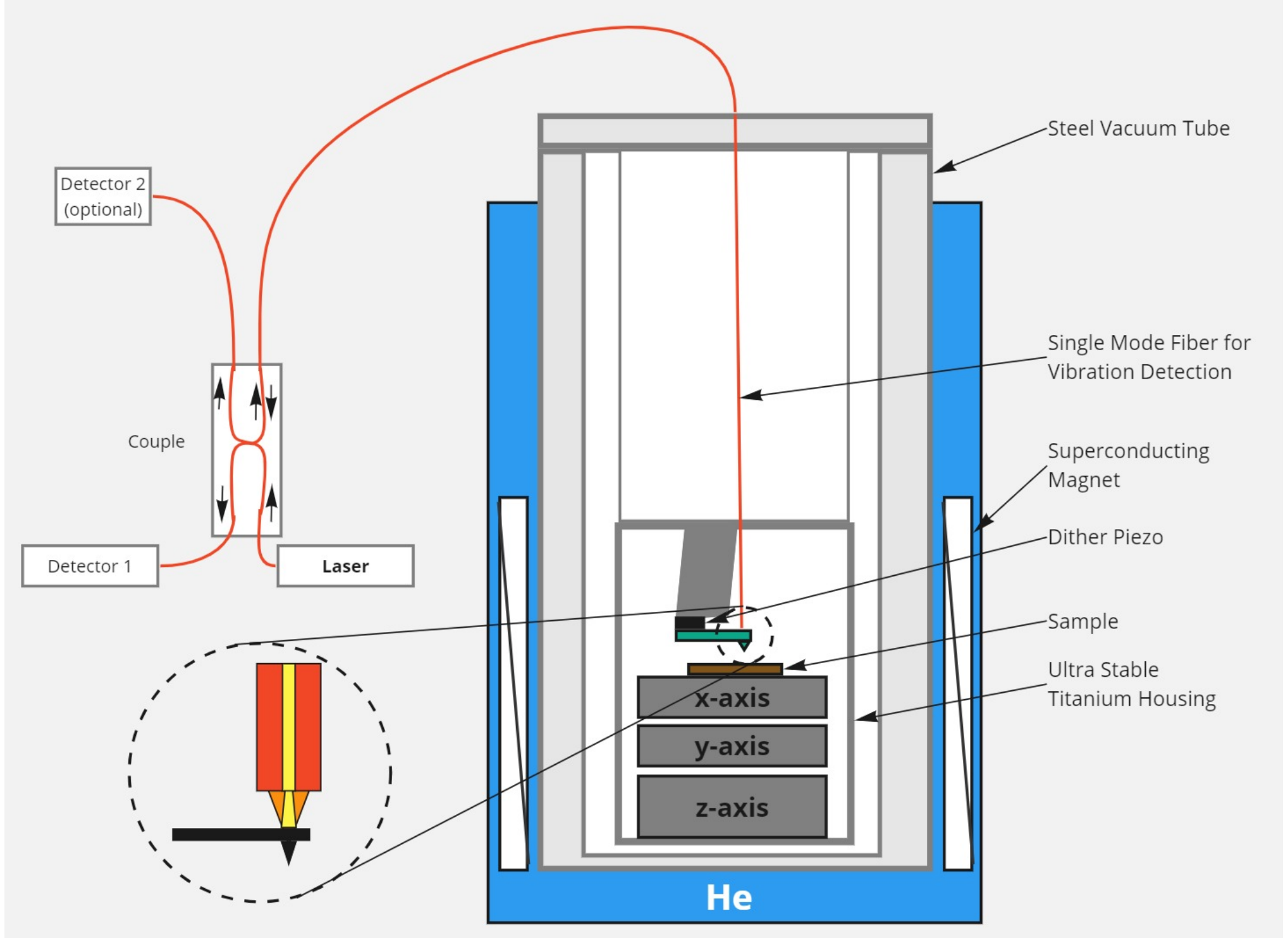


Scheme of MFM measurements (1).



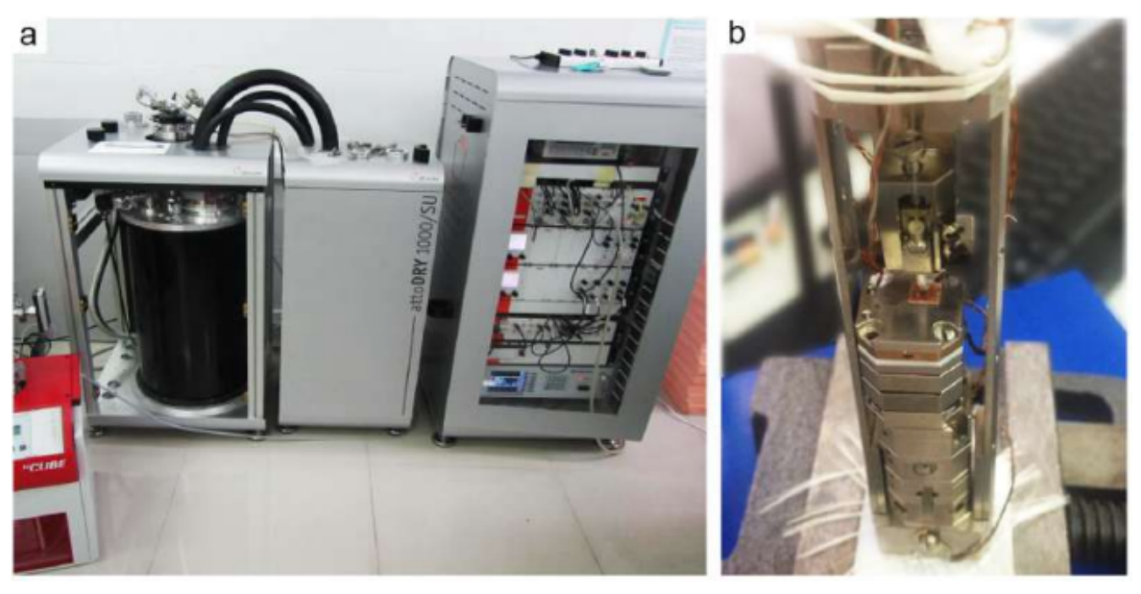
Principle of phase-detecting dynamic MFM (2).

Experimental setup



Scheme of AFM/MFM AttoDry1000

The experiments were carried out on an AttoCube AttoDry 1000 cryogenic scanning magnetic force microscope with a closed-loop cryogenic installation with a base temperature of 4 K.



AFM/MFM AttoDry1000 (a) - external view of the cryostat; (b) - working part of the probe with cantilever and sample

References

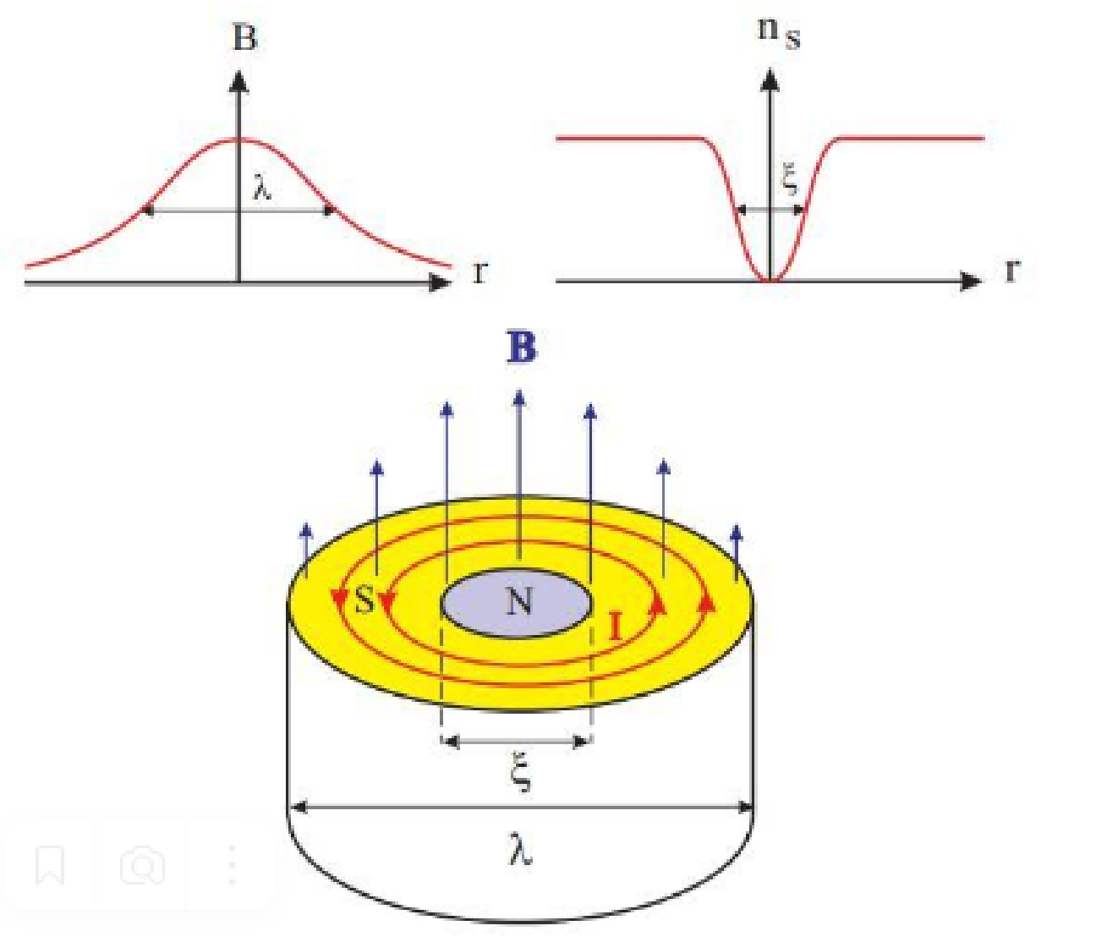
[1] Mironov, Victor. (2014). Fundamentals of Scanning Probe Microscopy.
[2] Passeri, Daniele Dong, Chunhua Reggente, Melania Angeloni, Livia Barteri, Mario Scaramuzzo, Francesca Angelis, Francesca Marinelli, Fiorenzo Antonelli, Flavia Rinaldi, Federica Marianecci, Carlotta Carafa, Maria Sorbo, Angela Sordi, Daniela Arends, Isabel Rossi, Marco. (2014). Magnetic force microscopy. Biomatter. 4. 10.4161/biom.29507.
[3] Rusakov, V. Chabanenko, V. Nabiałek, Adam Chumak, Oleksandr. (2017). The oscillation of the single Abrikosov's vortex in hard superconductors type II. Fizika Nizkikh Temperatur. 43. 843-859.

Abrikosov vortices in niobium films

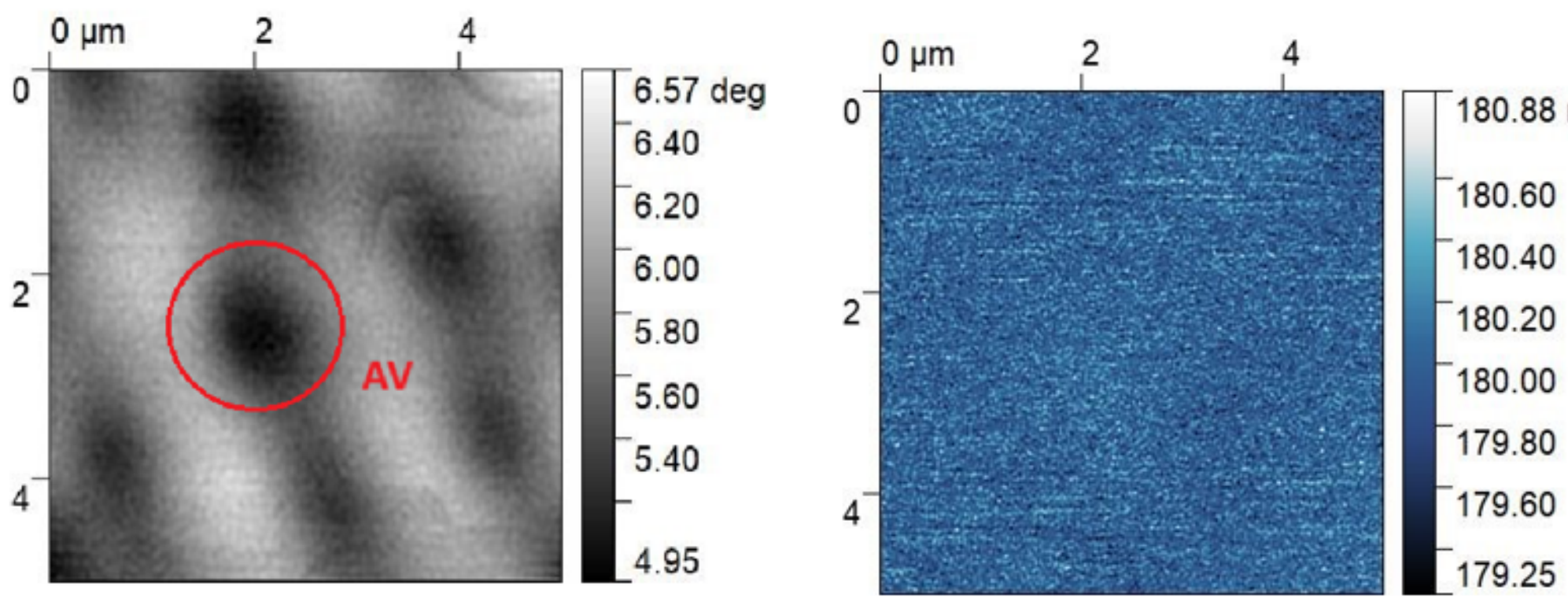
Abrikosov vortices are vortices of an overcurrent circulating around a normal core with a radius of the order of the coherence length ξ. These vortices induce a magnetic flux equal to the quantum of the magnetic flux. In an area with a radius of penetration depth λ, there is a shielding current.

Studies have shown that Abrikosov's magnetic vortices are localized mainly at grain boundaries that indicates the influence of the granular structure on the distribution of magnetic fields in the film. It was found that the pinning force of vortices depends on the size and orientation of the grains, as well as on the presence of defects in the film structure.

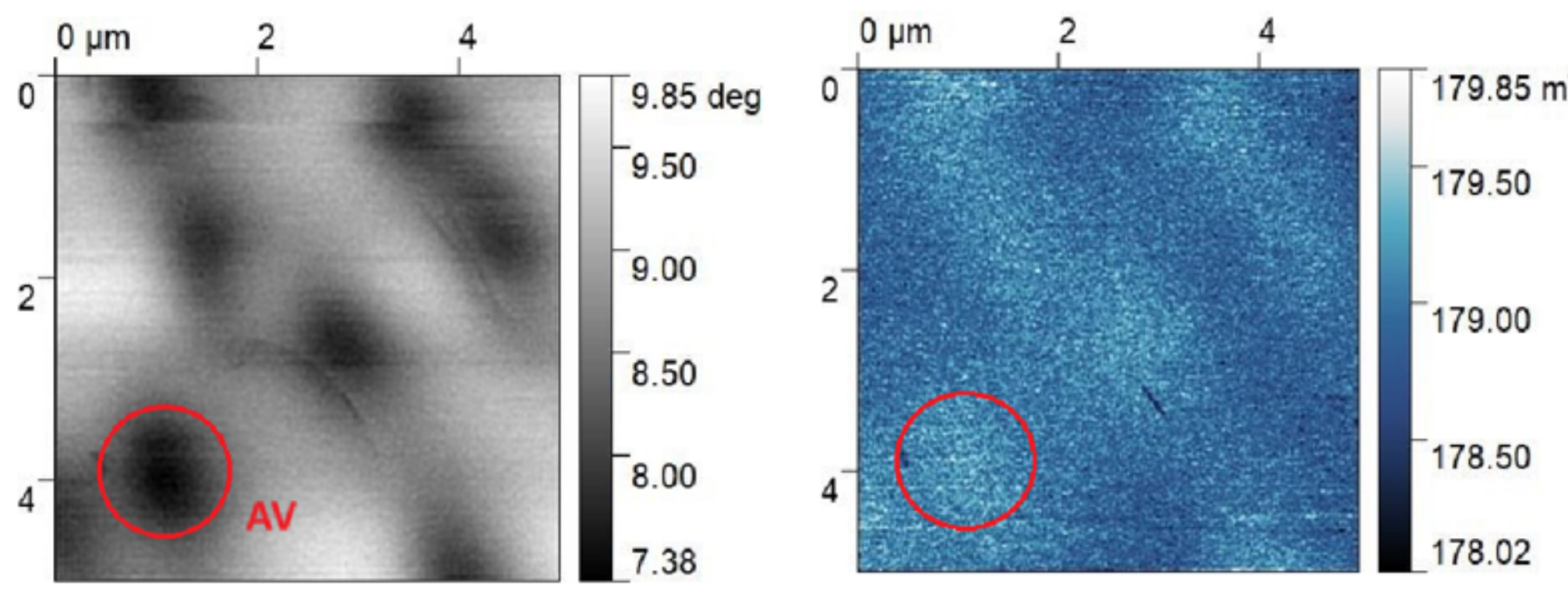
During the experiments, measurements were carried out at various temperatures, fields and lift of the cantilever.



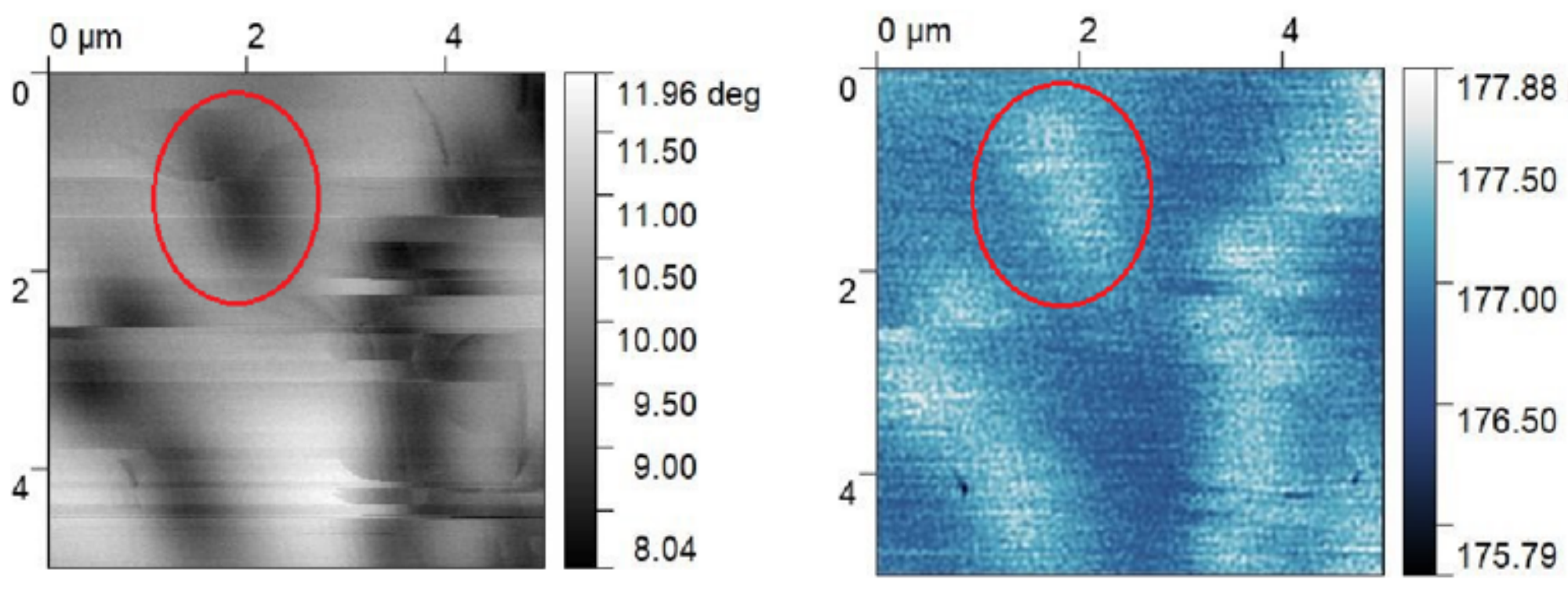
Structure of the Abrikosov vortex (3).



Phase (gray) and amplitude (blue) scans of niobium film with lift=200nm



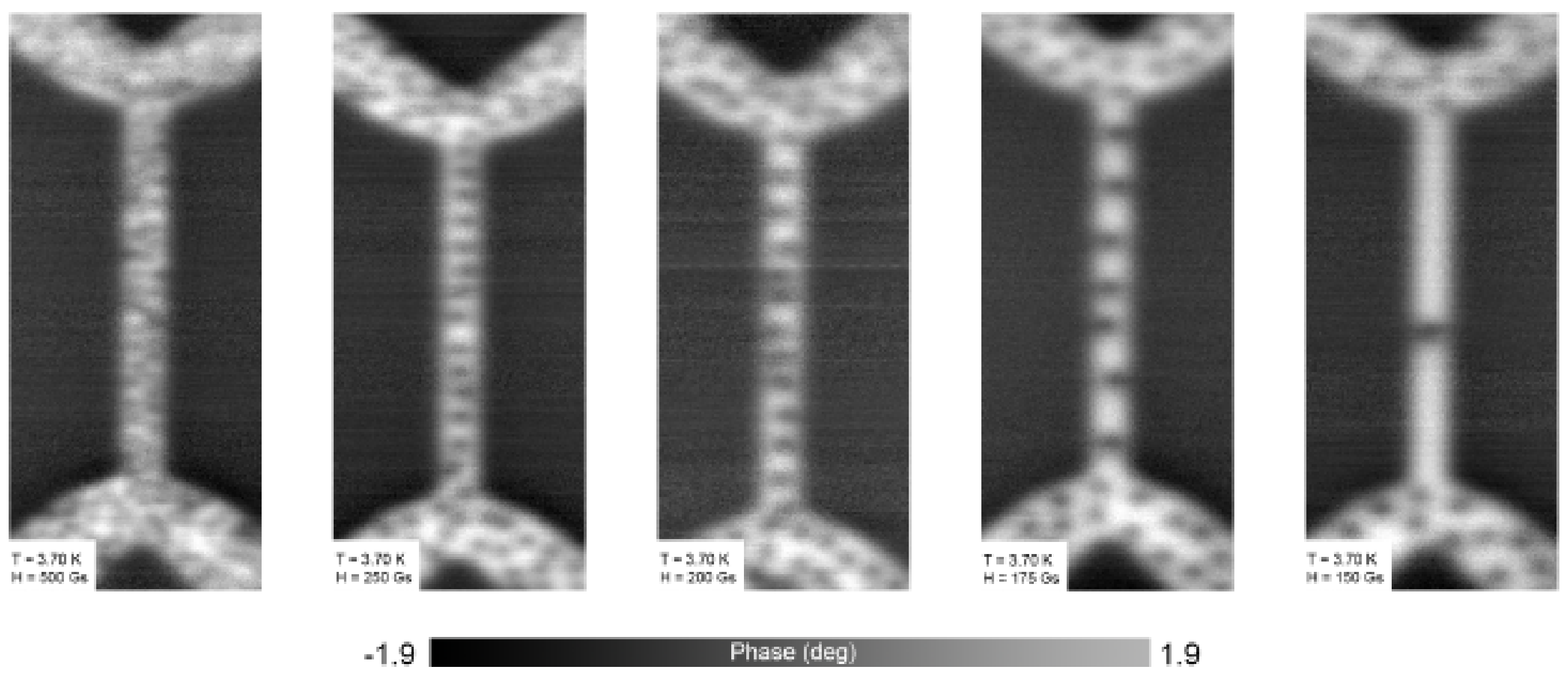
Phase (gray) and amplitude (blue) scans of niobium film with lift=150nm



Phase (gray) and amplitude (blue) scans of niobium film with lift=100nm

Superconducting bridge

MFM also allows not only to visualize Abrikosov vortices, but also to localize the defects on which they are pinned. This is especially important for understanding the internal structure of superconductors and improving their characteristics. Defects such as impurities, grain boundaries, and vacancies affect the behavior of vortices and, consequently, the magnetic and transport properties of superconducting structures.



Field Cooling in various magnetic fields

Conclusions

Magnetic force microscopy is an important and powerful tool for studying defects and the internal structure of superconducting materials. It allows you to visualize not only the magnetic structure, but also to get an idea of the defects. This provides valuable data for the development of new superconducting devices.

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